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FOR

PRECISION INPHASE/QUADRATURE

UP-DOWN CONVERTER STRUCTURES AND METHODS

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PRECISION INPHASE/QUADRATURE UP-DOWN CONVERTER STRUCTURES AND METHODS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to the field of frequency converters, as are commonly used in RF and other communication systems.

2. Prior Art

It is common in RF communications to place data to be transmitted on the inphase (I) and quadrature (Q) components of a baseband signal, to mix these components with the inphase and quadrature components of a local oscillator, and to combine the components so mixed for RF (or other) transmission. Similarly, on reception, the reverse process is carried out to recover the baseband I and Q components for recovery of the data. In the disclosure herein, the present invention will be described with respect to downconverters as used in RF receivers, though the invention is applicable to both downconverters and upconverters, whether for RF communication systems or other communication systems. Accordingly, for direct comparison purposes, the prior art with respect to downconverters will be discussed.

A typical prior art downconverter with $\omega_{LO} > \omega_{RF}$ for the unwanted image frequencies is illustrated in Figure 1. Mixers M1 and M2 mix the received RF signal $Cos((\omega_{RF}t)$ with mixer pumping signals comprising inphase (0°) and quadrature (-90°) components of the output of quadrature divider driven by a local oscillator signal $Cos(\omega_{LO}t)$ to recover the inphase (I) and the quadrature (Q) components of the baseband signal. However, in a typical receiver, there will be amplifiers and filters in each leg, not shown in Figure 1 for purposes of clarity but causing phase and amplitude errors in a real system, as well as mixer imperfections and imperfections in the orthogonality between the inphase and quadrature components of the output of the quadrature divider. These imperfections cause the appearance of image frequencies in the I and Q baseband signals, diminishing the accuracy of data recovery.

The foregoing imperfections may be categorized as a combination of two effects, namely phase shifts so that the I and Q baseband signals at the output of the downconverter (typically but not necessarily coupled to a digital signal processor (DSP)) are not truly orthogonal, and gain differences so that the I and Q baseband signals at the output of the downconverter do not have the same amplitude. The accumulated phase shifts may be lumped into an equivalent

phase shift between the inphase and quadrature components of the signals from the quadrature divider. Taking the inphase component of the quadrature divider signal as a reference, the phase errors may be lumped into the corresponding phase error in the quadrature component of the quadrature divider signal as follows:

$$\text{phase error} = 0^\circ / -(90^\circ + \Delta LO)$$

where: ΔLO = the cumulative phase error in the Q baseband signal relative to the I baseband signal.

The amplitude errors may be lumped as an amplitude error of the Q baseband signal relative to the I baseband signal, though it may be more instructive in light of a later analysis of the present invention to assign a conversion gain error to each of the I and Q component legs of the downconverter as follows:

Mixer M1 conversion gain error = $\Delta 1$

Mixer M2 conversion gain error = $\Delta 2$

PHASE ERROR ANALYSIS - PRIOR ART

Using the phase error assumption, the I and Q components output by mixers M2 and M1 of the converter of Figure 1, respectively, due to the lumped phase error ΔLO of a single quadrature divider ΔLO, are:

M1 (Q) $\frac{1}{2}\,\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t - (90^{\circ} + \Delta LO)\right]$

M2 (I) $\frac{1}{2}\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t\right]$

The effect of the phase error may be evaluated by running the output of the mixers through a quadrature combiner, actual in some systems, or simulated for purposes of performance analysis of the converter, as is shown in Figure 2. The Q component of the converter output would be shifted back 90 degrees by the quadrature combiner, so that the total output of a quadrature combiner for the unwanted image frequencies would be:

$$\frac{1}{2}\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t\right] + \frac{1}{2}\,\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t - (90^{\circ} + \Delta LO) - 90^{\circ}\right]$$

$$= \frac{1}{2}\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t\right] - \frac{1}{2}\,\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t - \Delta LO\right]$$

Or:

$$\frac{1}{2}\left\{\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t\right](1 - \mathrm{Cos}\Delta LO)\right\} - \frac{1}{2}\left\{\mathrm{Sin}\left[(\omega_{LO} - \omega_{RF})\,t\right]\mathrm{Sin}\Delta LO\right\}$$

Using the Taylor series expansions, assuming the phase errors are small:

$$\mathrm{Sin}(\Delta LO) = \Delta LO - \frac{(\Delta LO)^3}{3!} + \frac{(\Delta LO)^5}{5!} \ldots, \text{ and}$$

$$\mathrm{Cos}(\Delta LO) = 1 - \frac{(\Delta LO)^2}{2!} + \frac{(\Delta LO)^4}{4!} \ldots$$

The $\mathrm{Sin}[(\omega_{LO} - \omega_{RF})t]$ term in the unwanted image frequencies becomes:

$$1 - \mathrm{Cos}\,\Delta LO = -\frac{(\Delta LO)^2}{2!} + \frac{(\Delta LO)^4}{4!} \ldots$$

If, by way of example, ΔLO is 5 degrees, $(\Delta LO)^2/2!$ is $(5\pi/180)^2/2 = 0.0038$.

The $\mathrm{Sin}[(\omega_{LO} - \omega_{RF})t]$ term in the unwanted image frequencies due to a phase error in a conventional I/Q converter, proportional to $\mathrm{Sin}\,\Delta LO$, is not a small term, but a rather large term directly proportional to the phase error, namely:

$$\mathrm{Sin}(\Delta LO) = \Delta LO - \frac{(\Delta LO)^3}{3!} + \frac{(\Delta LO)^5}{5!} \ldots$$

Thus there is a first order (ΔLO) effect. For a 5 degree phase error, the error is $(5\pi/180) = 0.087$, or 8.7%.

AMPLITUDE ERROR ANALYSIS - PRIOR ART

Using the following mixer conversion gain errors and assuming no phase errors:

Mixer 1 conversion gain error = $\Delta 1$

Mixer 2 conversion gain error = $\Delta 2$

The output (Q) of the first mixer and its difference frequency term is:

$$(1+\Delta 1) * \mathrm{Cos}(\omega_{RF}t) * \mathrm{Cos}\left(\omega_{LO}t - 90^{\circ}\right)$$

$$\text{Difference frequency term} = \frac{1}{2}(1+\Delta 1)\mathrm{Sin}(\omega_{LO}t - \omega_{RF})t$$

The output (I) of the second mixer and its difference frequency term is:

$$(1+\Delta 2) * \mathrm{Cos}(\omega_{RF}t) * \mathrm{Cos}\left(\omega_{LO}t\right)$$

$$\text{Difference frequency term} = \frac{1}{2}(1+\Delta 2)\mathrm{Cos}(\omega_{LO}t - \omega_{RF})t$$

The output IRM_OUT of a quadrature combiner on the mixer outputs (Figure 2) for the image frequencies would be:

$$\frac{1}{2}(1+\Delta 1)\mathrm{Sin}\left[\left(\omega_{LO} - \omega_{RF}\right)t - 90^{\circ}\right]$$

$$+\frac{1}{2}(1+\Delta 2)\mathrm{Cos}\left(\omega_{LO} - \omega_{RF}\right)t$$

$$= \frac{1}{2}(\Delta 2 - \Delta 1)\ \mathrm{Cos}\left(\omega_{LO} - \omega_{RF}\right)t$$

If $(\Delta 2 - \Delta 1) = 0$, the image rejection will be perfect (IRM_OUT = 0 for the image frequencies). This illustrates the point that the important error is the gain mismatch between the two mixers. In most prior art systems, variable gain amplifier/attenuators are used to control the amplitudes of the I and Q signal outputs in unison, leaving the

difference in the mixer conversion gains as the important gain error parameter.

Prior art using double quadrature conversion mixers is described in "CMOS Mixers and Polyphase Filters for Large Image Rejection," authored by Farbod Behbahani et al. Starting on page 880, double quadrature upconversion is described. As shown in Fig. 17 on that page, the inputs to the four mixers are I_{in}, Q_{in}, $\overline{I_{in}}$ and $\overline{Q_{in}}$, with the outputs being I_{RF}, Q_{RF}, $\overline{I_{RF}}$ and $\overline{Q_{RF}}$. Thus at least one quadrature divider is required on the input side of the four mixers, adding an additional source of gain and phase errors over the present invention. Similarly, starting on page 881, quadrature downconversion is described, with double quadrature downconversion described on page 882. As shown in Fig. 20 on that page, a double quadrature downconverter in accordance with this prior art receives I and Q signal inputs, as well as I and Q mixer pumping inputs, to generate II + QQ and IQ + QI outputs, thus requiring a quadrature divider on the input to the downconverter. Particularly where the input is a high frequency such as an RF frequency, the quadrature divider also causes a high insertion loss, and a high noise figure for the downconverter. In the present invention, such quadrature dividers are not used, and the

image rejection is primarily dependent on the matching of errors in circuits, not the errors themselves.

BRIEF SUMMARY OF THE INVENTION

Precision inphase/quadrature up-down converter structures generally neither requiring trimming at the time of fabrication nor calibration during use. The converters use four mixers arranged to down convert to provide Q, I, $\overline{I}$ and Q baseband signals (or up convert Q, I, $\overline{I}$ and Q baseband signals), the combination of which signals has a very substantially reduced unwanted image frequency content. The use of an increased number of mixers in effect shifts the primary errors from absolute gain and phase errors, to gain and phase error mismatches between elements in replicated circuits, which mismatches can be held to a minimum in circuits replicated in a single integrated circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a diagram showing a typical prior art downconverter.

Figure 2 is a diagram of the typical prior art downconverter of Figure 1 with a quadrature combiner on the converter output.

Figure 3 is a block diagram of one embodiment of downconverter in accordance with the present invention.

Figure 4 is a block diagram of the embodiment of downconverter of Figure 3 with a quadrature combiner on the converter outputs.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to Figure 3, a block diagram of one embodiment of the present invention may be seen. As shown therein, an RF signal $\mathrm{Cos}(\omega_{RF}t)$ is applied to four mixers, M1 through M4. Again assuming, for purposes of illustration only, a down-converter with $\omega_{LO} > \omega_{RF}$ for the unwanted image frequencies, the second or pumping signal inputs to the mixers are provided by the 0 degree and -90 degree outputs of quadrature dividers LO2 and LO3 controlled by the 0 degree and -90 degree outputs of quadrature divider LO1, itself driven by a local oscillator signal $\mathrm{Cos}(\omega_{LO}t)$. The four mixer outputs are Q, I, $\bar{I}$ and Q. Neglecting any phase errors, it can be seen that the first Q (quadrature) output is generated by mixer M1 by mixing the RF signal $\mathrm{Cos}(\omega_{RF}t)$ with $\mathrm{Cos}(\omega_{LO}t)$ as shifted -90 degrees by quadrature divider LO2, the I (inphase) output is generated by mixer M2 by mixing the RF signal $\mathrm{Cos}(\omega_{RF}t)$ with $\mathrm{Cos}(\omega_{LO}t)$, the $\bar{I}$ (the inverse of inphase) output is generated by mixer M3 by mixing the RF signal $\mathrm{Cos}(\omega_{RF}t)$ with $\mathrm{Cos}(\omega_{LO}t)$ as shifted -90 degrees by quadrature divider LO1 and another -90 degrees by quadrature divider LO3, and the second Q (quadrature) output is generated by mixer M4 by mixing the RF signal $\mathrm{Cos}(\omega_{RF}t)$ with $\mathrm{Cos}(\omega_{LO}t)$ as shifted -90 degrees by quadrature divider LO1. The two Q components, of course, are ideally the same

quadrature component of the signal, but determined by the use of different quadrature dividers. Similarly, the I and $\bar{I}$ components are complementary inphase components of the signal, but again, determined by the use of different quadrature dividers.

Another way of looking at the outputs of each of the four mixers is to consider the effect of the respective output of quadrature divider LO1, and then the effect of the output of quadrature divider LO2 or LO3, as the case may be. For instance, the 0 degree output of quadrature divider LO1, would cause an inphase (I) output of a mixer, the -90 degree output of quadrature divider LO1 would cause a quadrature (Q) output of a mixer, the 0 degree output of quadrature divider LO2, would cause an inphase (I) output of a mixer, the -90 degree output of LO2 would cause a quadrature (Q) output of a mixer, etc. Using this analysis, the output of mixer M1 is IQ = Q, the output of mixer M2 is II = I, the output of mixer M3 is QQ = $\bar{I}$, and the output of mixer M4 is QI = Q.

The following are analyses of the effect of phase errors and amplitude errors in the converter to illustrate the advantages of the present invention.

PHASE ERROR ANALYSIS:

Since the inphase (0 degree) outputs of quadrature dividers LO1, LO2 and LO3 are essentially direct pass-throughs of the local oscillator signal $\mathrm{Cos}(\omega_{LO}t)$, assume there will not be any phase error in these components. The quadrature outputs (-90 degree components) however will have some phase error. Thus also assume:

$$\text{LO1 phase error} = 0^\circ / -(90^\circ + \Delta LO1)$$

$$\text{LO2 phase error} = 0^\circ / -(90^\circ + \Delta LO2)$$

$$\text{LO3 phase error} = 0^\circ / -(90^\circ + \Delta LO3)$$

With this assumption, the output (Q) of the first mixer is:

$$\mathrm{Cos}(\omega_{RF}t) * \mathrm{Cos}\left|\omega_{LO}t - (90^\circ + \Delta LO2)\right| =$$

$$\frac{1}{2}\left\{\mathrm{Cos}\left[(\omega_{RF} + \omega_{LO})t - (90^\circ + \Delta LO2)\right] + \mathrm{Cos}\left[(\omega_{RF} - \omega_{LO})t + (90^\circ + \Delta LO2)\right]\right\}$$

The output (I) of the second mixer is:

$$\mathrm{Cos}(\omega_{RF}t) * \mathrm{Cos}(\omega_{LO}t) =$$

$$\frac{1}{2}\left\{\mathrm{Cos}\left[(\omega_{RF} + \omega_{LO})t\right] + \mathrm{Cos}\left[(\omega_{RF} - \omega_{LO})t\right]\right\}$$

The output ($\bar{I}$) of the third mixer is:

$$\mathrm{Cos}(\omega_{RF}t) * \mathrm{Cos}\left|\omega_{LO}t - (90^\circ + \Delta LO1) - (90^\circ + \Delta LO3)\right| =$$

$$\frac{1}{2}\,\mathrm{Cos}\left[(\omega_{RF} + \omega_{LO})t - (90^{\circ} + \Delta LO1) - (90^{\circ} + \Delta LO3)\right]$$

$$+\ \frac{1}{2}\,\mathrm{Cos}\left[(\omega_{RF} - \omega_{LO})t + (90^{\circ} + \Delta LO1) + (90^{\circ} + \Delta LO3)\right]$$

The output (Q) of the fourth mixer is:

$$\mathrm{Cos}(\omega_{RF}t)\ *\ \mathrm{Cos}\left[\omega_{LO}t - (90^{\circ} + \Delta LO1)\right] =$$

$$\frac{1}{2}\left\{\mathrm{Cos}\left[(\omega_{RF} + \omega_{LO})t - (90^{\circ} + \Delta LO1)\right] + \mathrm{Cos}\left[(\omega_{RF} - \omega_{LO})t + (90^{\circ} + \Delta LO1)\right]\right\}$$

Only the difference frequency components are of interest in the exemplary embodiment, the sum frequency components being out of the passband of the system and thereby filtered out. The inphase signal output I_{out} is taken as the combined inphase signals, namely $I - \bar{I}$. Thus:

$$I_{out} = \frac{1}{2}\,\mathrm{Cos}(\omega_{RF} - \omega_{LO})t + \frac{1}{2}\,\mathrm{Cos}\left[(\omega_{RF} - \omega_{LO})t + \Delta LO1 + \Delta LO3\right]$$

The quadrature signal output Q_{out} is taken as the combined quadrature signals, namely Q + Q (see Figure 3). Thus:

$$Q_{out} = -\frac{1}{2}\,\mathrm{Sin}\left[(\omega_{RF} - \omega_{LO})t + \Delta LO2\right] - \frac{1}{2}\,\mathrm{Sin}\left[(\omega_{RF} - \omega_{LO})t + \Delta LO1\right]$$

The effect of the four mixer configuration of the present invention on the image frequencies may be seen by passing the signals through a quadrature combiner as shown in

Figure 4 to form an image rejection mixer, and then to look at the image remnants remaining. Since $\omega_{LO} > \omega_{RF}$ for the unwanted image frequencies in the example being described, and recognizing that $\mathrm{Cos}(-\theta) = \mathrm{Cos}(\theta)$, the difference frequency outputs for the four mixers can be rewritten as:

$$\text{M1} \quad (Q) \quad \frac{1}{2}\,\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t - (90^\circ + \Delta LO2)\right]$$

$$\text{M2} \quad (I) \quad \frac{1}{2}\,\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t\right]$$

$$\text{M3} \quad (\bar{I}) \quad \frac{1}{2}\,\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})t - \left(90^\circ + \Delta LO1\right) - \left(90^\circ + \Delta LO3\right)\right]$$

$$\text{M4} \quad (Q) \quad \frac{1}{2}\,\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t - (90^\circ + \Delta LO1\right]$$

The quadrature combiner will shift the Q components back 90 degrees and the $\bar{I}$ component back 180 degrees, and then combine the four signals for the quadrature combiner output IRM_OUT. Thus the output of the quadrature combiner for the image will be:

$$\frac{1}{2}\,\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t - (90^\circ + \Delta LO2) - 90^\circ\right]$$

$$+\frac{1}{2}\,\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t\right]$$

$$+\frac{1}{2}\,\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t - (90^\circ + \Delta LO1) - (90^\circ + \Delta LO3) - 180^\circ\right]$$

$$+\frac{1}{2}\,\mathrm{Cos}\left[(\omega_{LO} - \omega_{RF})\,t - (90^\circ + \Delta LO1) - 90^\circ\right]$$

Or:

$$-\frac{1}{2}\mathrm{Cos}\left[(\omega_{LO}-\omega_{RF})t-\Delta LO2\right]$$

$$+\frac{1}{2}\mathrm{Cos}\left[(\omega_{LO}-\omega_{RF})t\right]$$

$$+\frac{1}{2}\mathrm{Cos}\left[(\omega_{LO}-\omega_{RF})t-\Delta LO1-\Delta LO3\right]$$

$$-\frac{1}{2}\mathrm{Cos}\left[(\omega_{LO}-\omega_{RF})t-\Delta LO1\right]$$

Using the identity Cos(x + y) = Cos(x)Cos(y) - Sin(x)Sin(y), where $x = (\omega_{LO} - \omega_{RF})t$, this becomes:

$$\frac{1}{2}\mathrm{Cos}\left[(\omega_{LO}-\omega_{RF})t\right]\left[-\mathrm{Cos}\Delta LO2+1+\mathrm{Cos}(\Delta LO1+\Delta LO3)-\mathrm{Cos}\Delta LO1\right]$$

$$-\frac{1}{2}\mathrm{Sin}\left[(\omega_{LO}-\omega_{RF})t\right]\left[+\mathrm{Sin}\Delta LO2-\mathrm{Sin}(\Delta LO1+\Delta LO3)+\mathrm{Sin}\Delta LO1\right]$$

Or:

$$\frac{1}{2}\mathrm{Cos}\left[(\omega_{LO}-\omega_{RF})t\right]\left[1-\mathrm{Cos}\Delta LO2+\mathrm{Cos}(\Delta LO1+\Delta LO3)-\mathrm{Cos}\Delta LO1\right]$$

$$+\frac{1}{2}\mathrm{Sin}\left[(\omega_{LO}-\omega_{RF})t\right]\left[\mathrm{Sin}(\Delta LO1+\Delta LO3)-\mathrm{Sin}\Delta LO2-\mathrm{Sin}\Delta LO1\right]$$

For perfect image rejection:

$1-\mathrm{Cos}\Delta LO2+\mathrm{Cos}(\Delta LO1+\Delta LO3)-\mathrm{Cos}\Delta LO1=0$, and

$\mathrm{Sin}(\Delta LO1+\Delta LO3)-\mathrm{Sin}\Delta LO2-\mathrm{Sin}\Delta LO1=0$

If $\Delta LO2 = \Delta LO3 = 0$, or if $\Delta LO1 = 0$, there will be perfect image rejection. Also if $\Delta LO2 = \Delta LO3 << \Delta LO1$, there will be nearly perfect image rejection. Most important, however, is the case where the phase errors for the three quadrature dividers are non-zero, but equal. In an integrated circuit, it is much easier to match circuit phase errors by simply replicating the same circuit, than it is to try to eliminate the phase error in a single circuit, unit to unit, over the temperature operating range, etc. Thus with this assumption:

$$\Delta LO2 = \Delta LO3 = \Delta LO1 = \Delta LO$$

Now the image rejection will be proportional to:

$$1 - 2\mathrm{Cos}\Delta LO + \mathrm{Cos}(2\Delta LO), \text{ and}$$

$$\mathrm{Sin}2\Delta LO - 2\mathrm{Sin}\Delta LO$$

Using the Taylor series expansions, again assuming the phase errors are small:

$$\mathrm{Sin}(\Delta LO) = \Delta LO - \frac{(\Delta LO)^3}{3!} + \frac{(\Delta LO)^5}{5!} \ldots, \text{ and}$$

$$\mathrm{Cos}(\Delta LO) = 1 - \frac{(\Delta LO)^2}{2!} + \frac{(\Delta LO)^4}{4!} \ldots$$

the foregoing equations become:

$$1 - 2\mathrm{Cos}\Delta LO + \mathrm{Cos}(2\Delta LO) = 1 - (2 - \frac{2(\Delta LO)^2}{2!} + \frac{2(\Delta LO)^4}{4!} \ldots)$$

$$+\ (1 - \frac{4(\Delta LO)^2}{2!} + \frac{16(\Delta LO)^4}{4!} \ldots) = -(\Delta LO)^2 + \frac{7(\Delta LO)^4}{12} \ldots,$$

and

$$Sin2\Delta LO - 2Sin\Delta LO = 2(\Delta LO) - \frac{8(\Delta LO)^3}{3!} + \frac{32(\Delta LO)^5}{5!} \ldots$$

$$-\ (2(\Delta LO) - \frac{2(\Delta LO)^3}{3!} + \frac{2(\Delta LO)^5}{5!} \ldots)$$

$$= -(\Delta LO)^3 + \frac{(\Delta LO)^5}{4} \ldots$$

Thus if $\Delta LO1 = \Delta LO2 = \Delta LO3 = \Delta LO$, the undesired image will be present to the extent of:

$$\frac{1}{2} Cos[(\omega_{LO} - \omega_{RF})t](-(\Delta LO)^2 + \frac{7(\Delta LO)^4}{12} \ldots), \text{ and}$$

$$\frac{1}{2} Sin[(\omega_{LO} - \omega_{RF})t](-(\Delta LO)^3 + \frac{(\Delta LO)^5}{4} \ldots)$$

This may be compared to the I and Q components in the prior art (such as the outputs of the mixers M2 and M1 of Figure 1, respectively), due to a phase error ΔLO of a single quadrature divider. The I and Q components, generalized as to a general phase error ΔLO as described in the prior art section, are:

$$M1 \quad (Q) \quad \frac{1}{2} Cos[(\omega_{LO} - \omega_{RF})t - (90^\circ + \Delta LO)]$$

$$M2 \quad (I) \quad \frac{1}{2} Cos[(\omega_{LO} - \omega_{RF})t]$$

The Q component would be shifted back 90 degrees by a quadrature combiner, so that the total output of a quadrature combiner would be:

$$\frac{1}{2}\mathrm{Cos}\left[(\omega_{LO}-\omega_{RF})t\right] + \frac{1}{2}\mathrm{Cos}\left[(\omega_{LO}-\omega_{RF})t-(90^{\circ}+\Delta LO)-90^{\circ}\right]$$

$$= \frac{1}{2}\mathrm{Cos}\left[(\omega_{LO}-\omega_{RF})t\right] - \frac{1}{2}\mathrm{Cos}\left[(\omega_{LO}-\omega_{RF})t-\Delta LO\right]$$

Or:

$$\frac{1}{2}\left\{\mathrm{Cos}\left[(\omega_{LO}-\omega_{RF})t\right](1-\mathrm{Cos}\Delta LO)\right\} - \frac{1}{2}\left\{\mathrm{Sin}\left[(\omega_{LO}-\omega_{RF})t\right]\mathrm{Sin}\Delta LO\right\}$$

Thus the magnitude of the $1 - \mathrm{Cos}\Delta LO$ term due to a phase error in a conventional I/Q converter is to be compared with the magnitude of the $1 - 2\mathrm{Cos}\Delta LO + \mathrm{Cos}(2\Delta LO)$ term due to a uniform phase error in a four mixer I/Q converter in accordance with the present invention, and the magnitude of the $\mathrm{Sin}\Delta LO$ term due to a phase error in a conventional I/Q converter is to be compared with the magnitude of the $\mathrm{Sin}2\Delta LO - 2\mathrm{Sin}\Delta LO$ term due to a uniform phase error in a four mixer I/Q converter in accordance with the present invention. Using the foregoing Taylor series expansion for the $\mathrm{Cos}\Delta LO$ term:

$$1 - \mathrm{Cos}\Delta LO = -\frac{(\Delta LO)^2}{2!} + \frac{(\Delta LO)^4}{4!}\ldots$$

$$1 - 2\text{Cos}\Delta\text{LO} + \text{Cos}(2\Delta\text{LO}) = -(\Delta\text{LO})^2 + \frac{7(\Delta\text{LO})^4}{12}\ldots$$

Thus assuming ΔLO is fairly small, the magnitude of the $\text{Cos}[(\omega_{LO} - \omega_{RF})t]$ term in the unwanted image frequencies has been increased by use of the present invention by a factor of 2. However this term is small anyway if ΔLO is reasonably small. By way of example, if ΔLO is 5 degrees, $(\Delta\text{LO})^2$ is $(5\pi/180)^2 = 0.0076$ compared to 0.0038 for a conventional converter with the same phase error.

The $\text{Sin}[(\omega_{LO} - \omega_{RF})t]$ term in the unwanted image frequencies due to a phase error in a conventional I/Q converter (proportional to SinΔLO) is not a small term, but a rather large term directly proportional to the phase error. Comparing the magnitude of the SinΔLO term due to a phase error in a conventional I/Q converter with the magnitude of the Sin2ΔLO − 2SinΔLO term due to a uniform phase error in a four mixer I/Q converter in accordance with the present invention:

$$\text{Sin}(\Delta\text{LO}) = \Delta\text{LO} - \frac{(\Delta\text{LO})^3}{3!} + \frac{(\Delta\text{LO})^5}{5!}\ldots, \text{ and}$$

$$\text{Sin}2\Delta\text{LO} - 2\text{Sin}\Delta\text{LO} = -(\Delta\text{LO})^3 + \frac{(\Delta\text{LO})^5}{4}\ldots$$

Thus a first order (ΔLO) effect has been reduced by the present invention to a third order $((\Delta\text{LO})^3)$ effect, reducing

the effect for a 5 degree phase error from a $(5\pi/180) = 0.087$ effect to a $(5\pi/180)^3 = 0.00066$ effect.

In summary, for the 5 degree phase error illustrative example used herein, the largest term in the unwanted image frequencies due to a phase error in a conventional I/Q converter is 0.087, whereas the largest term in a four mixer I/Q converter in accordance with the present invention is 0.0076, an improvement by more than an order of magnitude.

The improvement in the suppression of image frequencies, or in the rejection of the image itself just illustrated was based on being able to achieve uniform phase errors in the three quadrature dividers ($\Delta LO1 = \Delta LO2 = \Delta LO3 = \Delta LO$) with some degree of accuracy. This is much more readily achievable than a very low phase error in one quadrature divider, particularly in an integrated circuit, as one only has to replicate the same quadrature divider structure for the three quadrature divider circuits, preferably the three phase shifters being close to each other on the integrated circuit. While the phase errors of the phase shifters will differ, integrated circuit to integrated circuit, and will drift with temperature, and to some extent with time, all three phase shifters on a particular integrated circuit will match and drift together without trimming for alignment, or calibration during use. As long as the phase errors of the

three phase shifters are substantially equal, the magnitude of the phase errors doesn't matter much, provided the phase errors remain within reasonable and readily achievable limits.

AMPLITUDE ERROR ANALYSIS

Figures 3 and 4 are simplified diagrams for a typical converter in accordance with the present invention, in that the output circuits of the mixers will typically include amplifiers and filters, both of which will effect the amplitude of the ultimate I/Q output signals. These errors can be lumped with the conversion gain errors of the mixers and represented by an overall conversion gain error for each I/Q path. Thus normalizing the desired gain to unity, the overall mixer conversion gain errors can be represented as follows:

Mixer M1 conversion gain error = $\Delta 1$

Mixer M2 conversion gain error = $\Delta 2$

Mixer M3 conversion gain error = $\Delta 3$

Mixer M4 conversion gain error = $\Delta 4$

Assuming the foregoing conversion gain errors but no phase errors, the output (Q) of the first mixer and its difference frequency term is:

$$(1+\Delta 1) * \mathrm{Cos}(\omega_{RF}t) * \mathrm{Cos}\left(\omega_{LO}t - 90^\circ\right)$$

$$\text{Difference frequency term} = \frac{1}{2}(1+\Delta 1)\text{Sin}(\omega_{LO}t - \omega_{RF})t$$

The output (I) of the second mixer is:

$$(1+\Delta 2) * \text{Cos}(\omega_{RF}t) * \text{Cos}(\omega_{LO}t)$$

$$\text{Difference frequency term} = \frac{1}{2}(1+\Delta 2)\text{Cos}(\omega_{LO}t - \omega_{RF})t$$

The output ($\bar{I}$) of the third mixer is:

$$(1 + \Delta 3) * \text{Cos}(\omega_{RF}t) * \text{Cos}(\omega_{LO}t - 180^\circ)$$

$$\text{Difference frequency term} = -\frac{1}{2}(1+\Delta 3)\text{Cos}(\omega_{LO}t - \omega_{RF})t$$

The output (Q) of the fourth mixer is:

$$(1 + \Delta 4) * \text{Cos}(\omega_{RF}t) * \text{Cos}(\omega_{LO}t - 90^\circ)$$

$$\text{Difference frequency term} = \frac{1}{2}(1+\Delta 4)\text{Sin}(\omega_{LO}t - \omega_{RF})t$$

The output IRM_OUT for the image frequencies will be:

$$\frac{1}{2}(1+\Delta 1)\text{Sin}\left[(\omega_{LO} - \omega_{RF})t - 90^\circ\right]$$

$$\frac{1}{2}(1+\Delta 2)\text{Cos}(\omega_{LO} - \omega_{RF})t$$

$$-\frac{1}{2}(1+\Delta 3)\text{Cos}\left[(\omega_{LO} - \omega_{RF})t - 180^\circ\right]$$

$$+\frac{1}{2}(1+\Delta 4)\text{Sin}\left[(\omega_{LO} - \omega_{RF})t - 90^\circ\right]$$

$$= \frac{1}{2}(\Delta 2 + \Delta 3 - \Delta 1 - \Delta 4)\ \mathrm{Cos}\left(\omega_{LO} - \omega_{RF}\right)t$$

If $(\Delta 2 + \Delta 3 - \Delta 1 - \Delta 4) = 0$, the image rejection will be perfect (IRM_OUT = 0 for the image frequencies). Thus:

IRM_OUT = 0 when $\Delta 1 = \Delta 2$ and $\Delta 3 = \Delta 4$,

IRM_OUT = 0 when $\Delta 2 + \Delta 3 = \Delta 1 + \Delta 4$,

IRM_OUT = 0 when $\Delta 1 + \Delta 3$ and $\Delta 2 = \Delta 4$, and

IRM_OUT = 0 when $\Delta 1 - \Delta 2 = \Delta 3 - \Delta 4$

As in the prior art, the important term is the difference in conversion gain errors, though with the present in invention, there should be some reduction in the effect of the conversion gain errors on the unwanted image frequencies because of the averaging effect resulting from the use of 4 mixers in the present invention as opposed to just the 2 mixers of the prior art.

The exemplary embodiments of the invention have been described in detail with respect to downconverters wherein $\omega_{LO} > \omega_{RF}$ for the unwanted image frequencies ($\omega_{RF} > \omega_{LO}$ for the wanted frequencies). It will be recognized by those skilled in the art however, that the invention is equally applicable to downconverters wherein $\omega_{RF} > \omega_{LO}$ for the unwanted image frequencies, and $\omega_{LO} > \omega_{RF}$ for the wanted

frequencies, by simply making certain phase changes (reversals) in the downconverter.

The invention is applicable to downconverters wherein the I and Q outputs are baseband signals. Using a quadrature combiner as in the embodiment of Figure 4, an image rejection mixer is provided for providing a downshifted (or an up-shifted) intermediate frequency (IF) substantially free of image frequencies. The invention is also directly applicable to upconverters, wherein the I and Q components of a baseband signal is applied to the mixers, the outputs of which are combined to provide an RF (or intermediate frequency) signal, such as for transmission. In general, not only will the quadrature dividers be formed by replicating a single quadrature divider circuit on a single integrated circuit, but also the mixers, and the amplifiers and filters in each mixer leg will be replicated circuits, so that the overall or lumped phase errors will be as equal as possible and track each other over temperature changes, etc., as will amplitude mismatches. Thus while certain preferred embodiments of the present invention have been disclosed in detail herein, such disclosure has been for purposes of illustration and not for purposes of limitation. Thus various changes in form and detail of the present invention will be obvious to those skilled in the art without departing from the spirit and scope of the invention.